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# Optioneering analysis for connecting Dogger Bank offshore wind farms to the GB electricity network

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This paper outlines possibilities for connecting 2.4 GW of power from two separate wind farms at Dogger Bank in the North Sea to the GB transmission system in Great Britain. Three options based on HVDC with Voltage Source Converters (VSC HVDC) are investigated: two separate point-to-point connections, a four-terminal multi-terminal network and a four-terminal network with the addition of an AC auxiliary cable between the two wind farms. Each option is investigated in terms of investment cost, controllability and reliability against expected fault scenarios. The paper concludes that a VSC-HVDC point-to-point connection is the cheapest option in terms of capital cost and has the additional advantage that it uses technology that is commercially available. However, while multi-terminal connections are more expensive to build it is found that they can offer significant advantages over point to point systems in terms of security of supply and so could offer better value for money overall. A multi-terminal option with an auxiliary AC connection between wind farms is found to be lower cost than a full multi-terminal DC grid option although the latter network would offer ability to operate at greater connection distances between substations.



## 1. Introduction

The increasing demand for wind power production and reduced visual impact is driving the development of offshore wind farms. The GB Government has issued plans to install more than 40 GW of renewable power generation by 2020, with most of the energy being delivered from new offshore wind farms around the coast of Great Britain [1–3]. The Dogger Bank Round 3 offshore site in the North Sea is expected to be the largest, with an initial planned capacity of 7.2 GW [4].

Due to higher wind speeds and abundant open areas offshore wind farms are seen as a promising option for large-scale power generation. However, the harsh offshore environment and large distance from the mainland grids represent a significant challenge to be overcome. Achieving this may require the use of high-specification wind turbines that can be operated remotely, with more reliable control systems since these are at present the biggest single source of failures in wind turbines [5]. Efficient and reliable transmission systems which permit power transfer with reduced losses and minimum operational issues for mainland grids will also be required.

Offshore wind farms can be connected to onshore grids using AC or DC transmission. The maximum economic distance for the AC transmission option is limited by the need for appropriately sized and located reactive compensation as well as the need for measures to deal with transient over-voltages and harmonic resonance [4,6]. A DC transmission system is an option which minimises the impact of onshore grid disturbances on offshore power production due to a decoupled connection between the wind farms and the onshore grid [7,8]. Another advantage of a DC system is that onshore converter stations can be used to provide additional services such as reactive power provision to the onshore grid at no additional cost; in some cases, independent of wind power production offshore [9].

Many offshore wind farms will be located a significant distance from the shore, including most of the Crown Estate Round 3 sites [10]. Due to the high potential capacity of Dogger Bank and the long distance to shore (a minimum of 144 km), HVDC transmission is seen as the only viable option for transferring the power back to the onshore transmission system. Two different HVDC technologies are available: voltage source converters using IGBTs (VSC-HVDC) and line-commutated converter (LCC-HVDC). VSC-HVDC has several

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technical advantages over LCC-HVDC. For example the use of self-commutated semiconductors removes the need for communication systems for power transfer, VSC has black start capability unlike LCC making it preferable for connection to 'weak' AC grids like offshore wind farms. Furthermore there is no requirement for harmonic filters and other compensation equipment such as STATCOMs meaning there is less space required on the offshore platform. VSC-HVDC also offers a high level of controllability which allows for the use of multi-terminal topologies [11,12].

In Refs. [13,14] it is shown that a point-to-point VSC-HVDC connection improves voltage quality in the grid compared with an AC connection where wind variation may cause propagation of voltage fluctuations. This work also highlights the advantages of decoupled operation of the transmission system and investigates different potential control strategies. In this paper the AC voltage is controlled at the wind farm level taking account the wind variation. Multi-terminal VSC-HVDC is studied in Refs. [15,16] in terms of flexible control capabilities and as a future option for connecting a large amount of power from offshore wind farms. These studies suggest that this is a very attractive option for interconnection between countries and also for connection of offshore oil and gas platforms. A VSC-HVDC transmission system with additional AC auxiliary cables providing a connection between wind farms is a promising solution if the distance between the wind farm substations isn't too great and a variety of options have been shown in studies conducted by National Grid [4]. It is already a well-known technology and that may improve system reliability and security in a more cost effective way.

VSC-HVDC is a relatively young technology but the scale of delivered and planned projects is advancing rapidly to the point that it can compete with long established and high power LCC-HVDC technology. The ABB NordLink connection proposes the largest point to point connection between two onshore locations and will consist of a 1400 MW, ±525 kV bipole connection between Norway and Germany [17]. In 2013 the 400 MW, ±150 kV Borwin1 connection to the Bard1 German offshore wind farm was the first VSC-HVDC scheme to connect an offshore wind farm to shore. In addition to this even larger projects are under development in the German offshore sector such as the 900 MW, ±320 kV Dolwin2 project [18]. Early VSC-HVDC projects were based on two or three level converter technology using pulse width modulation however it is likely that newer modular multilevel technology will be preferred in most future developments due to reduced losses and station footprint [19,20].

This paper seeks to investigate the merits of different connection options for far offshore wind farm installations including the possibility of introducing interconnection between two wind farms in relatively close proximity. It does this by exploring three VSC-HVDC connection schemes designed to transfer 2.4 GW of power from two separate Dogger Bank wind farms to the GB transmission system in Great Britain (GB). The study is based on option 1 from the National Grid "Round 3 Offshore Wind Farm Connection Study" shown in Fig. 1 [21]. The studies focus on connecting wind farm 1 and wind farm 2 to the onshore grid with each farm sized at 1.2 GW. The magnitude of power flows into the GB network suggests the use of two onshore connection points [21], and the scenarios presented in this study are based on this assumption.

The options considered are as follows:

(i) two separate point-to-point connections;
(ii) a multi-terminal VSC-HVDC network; and
(iii) point-to-point connections with an additional AC cable linking the two wind farms

Each option is described in detail together with the advantages that each provides. A thorough cost analysis of the electrical connection infrastructure is carried out for each option using estimates for component costs that are validated by industry experts. A cost-benefit analysis is then carried out by estimating the level and value of undelivered energy due to expected fault conditions over the project lifetime and comparing against the capital cost analysis.

The remainder of this paper is structured as follows: Section 2 describes the case study and arrangement of proposed connections and lays out the cost assumptions common to the three test cases. Sections 3–6 describe the three test cases and calculate the costs of each. Section 7 shows the results of a Monte Carlo-based reliability analysis that investigates how each option handles a lifetime of expected fault conditions in terms of their ability to deliver energy to shore and the paper ends with a discussion and conclusion section.

## 2. Case study

A project to build and connect wind generation in Dogger Bank to the GB mainland grid can be split into two systems: the wind farm system and the transmission systems. In this paper the wind farm system is assumed to consist of two separate 1.2 GW wind farms within the Dogger Bank area as shown in Fig. 1. The internal structure of the wind farms from the turbines to the AC to DC conversion is the same for all cases. Each wind farm consists of 240 5 MW turbines connected at 33 kV by HVAC inter-array cabling in strings of no greater than 9 wind turbines connected to the AC collector station. Two AC offshore collector stations and a single offshore converter station are constructed at each wind farm. The collector and converter stations are connected at 275 kV. The converter station houses the VSC-HVDC technology, gas insulated switchgear, advanced control and protection systems.

The converter station represents the point-of-connection of the wind farm system to the transmission system, and is itself assumed to be part of the transmission system. The converter station links to either the point-to-point or multi-terminal HVDC networks and in option 3, on the AC side, to the AC-auxiliary cable linking the converter stations of the two wind farms at 275 kV.

In this paper, costs are estimated through consultation with a UK-based Engineering Design firm and industry experts with significant offshore wind farm experience and therefore represent industry estimates. Installation costs for the turbines have been verified with 3 wind turbine manufacturers that produce turbines of the desired specification. All cabling costs for the project are shown in Table 1. Cables cost between £1 M per kilometre (33 kV Offshore AC Cable) and £2.5 M per kilometre (275 kV HVAC Offshore Cable). Wind farm internal costs are shown in Table 2. Transportation includes one-off costs for installation of accommodation, daily costs for transportation of employees from accommodation to site and monthly costs for changes in working groups.

Costs presented for the converter stations and wind turbines are the installed costs which include all civil works. Additional civil works are also included as separate items in the cost analysis where they are not directly related to individual items.

The costs associated with the internal wind farm infrastructure are the same for all three options. These fixed costs include: the wind turbines, 33 kV inter-array cables, AC collector platforms, and 275 kV cable between collector and converter stations, the civil/construction works and transport. The cost of the converter station is assumed to be part of the costs of the transmission system.

At the point of connection to the onshore grid, all options must deliver power at 400 kV AC and much of the shore infrastructure will be the same for the three options investigated. The costs associated with these aspects of the project are included in the cost

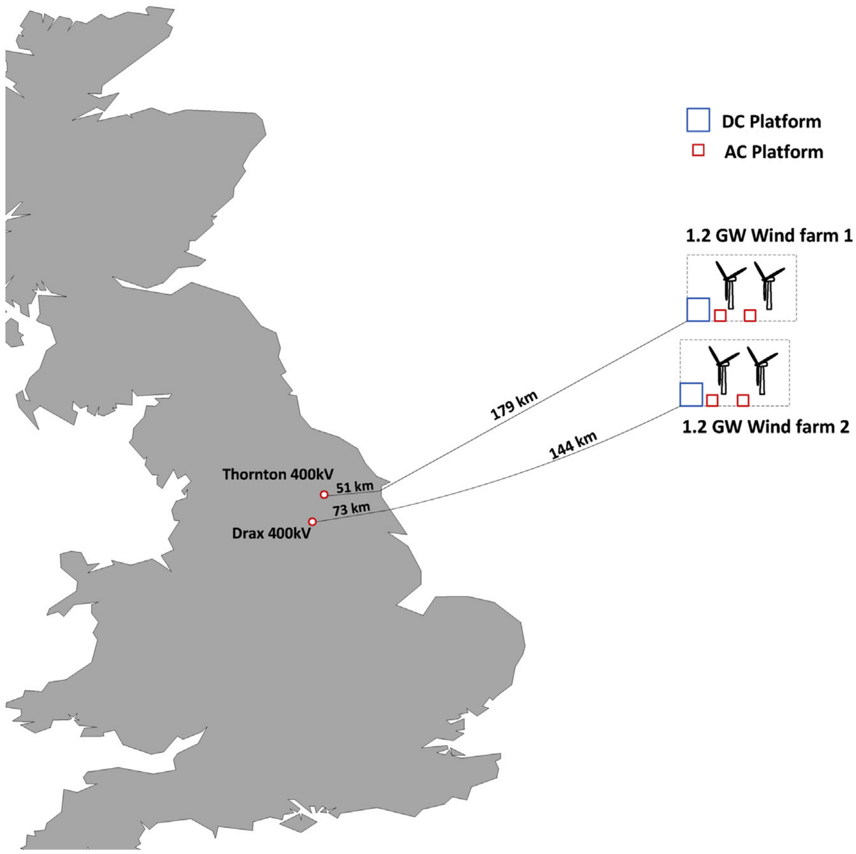


**Fig. 1.** Dogger Bank connection overview based on [21].

**Table 1**
Cables costs breakdown in £M.

| Cables | Price £M |
|---|---|
| VSC-HVDC Offshore **Cable ± 320 kV** | 1.1/km |
| HVAC Offshore Cable 33 kV Inter-array to collector | 1/km |
| HVAC Offshore Cable 275 kV Collector to Converter | 2.5/km |
| HVAC Onshore Cable 275 kV to transformer and 400 kV to grid | 2.5/km |

**Table 2**
Costs associated with the internal wind farm infrastructure in £M [22].

| Item | Unit price | Quantity | Total cost |
|---|---|---|---|
| 5 MW Offshore WT | 6.6 | 480 | 3168 |
| 33 kV inter-array cable (£M/km) | 1 | 538 | 538 |
| 275 kV AC cable (£M/km) | 2.5 | 15 | 37.5 |
| AC collector Station | 100 | 4 | 400 |
| Added Civil/Construction Works | | | 5.25 |
| Transport | | | 2.9 |
| Accommodation | | | 6 |
| Total | | | 4171 |

estimates for each option.

## 3. Case 1 − Two point-to-point VSC-HVDC links

This case, which represents the base-case, investigates a point-to-point connection which involves connecting each of the two wind farms separately with point-to-point VSC-HVDC links via ± 300 kV symmetrical monopole configuration. The two wind farms and their related electrical infrastructure operate as separate systems up to the point of connection with the GB National Grid as shown in Fig. 2.

The transmission system for each wind farm includes a fully-sized VSC-HVDC converter capable of converting the full output of that wind farm. After the conversion to DC at ± 300 kV, power will flow through an HVDC subsea cable to the GB coastline. Crossing structures will be necessary where cables cross existing subsea installations. Underground onshore DC cables will be laid between the foreshore and the onshore DC/AC converter station which will require up to 3 ha of land and may be up to 30 m in height. AC underground cables will then export power from the inverter to National Grid 400 kV substations at Thornton and Drax after which point control lies with National Grid. As shown in Fig. 1, the grid connections points are a significant distance from the shore, with Drax situated 73 km inland and Thornton 51 km this topology and point of connections are based on option 1connection overview from National Grid [21]. The onshore converter stations will be located near the grid connection point.

The VSC-HVDC connection as shown in Fig. 2, has been previously used in onshore and offshore applications, furthermore many different projects this kind are under development or planned [23–26]. There is a growing interest in this technology as a means of integrating offshore wind power plant to onshore grid.

The main advantages of using VSC-HVDC point to point connection compared with the classical LCC-HVDC connections are as follows [4,27–30]:

- A point-to-point connection with a VSC-HVDC system as opposed to classical LCC-HVDC connection provides the ability to expand the network later to greater capacities, for example if further wind farm development occurs close to the existing

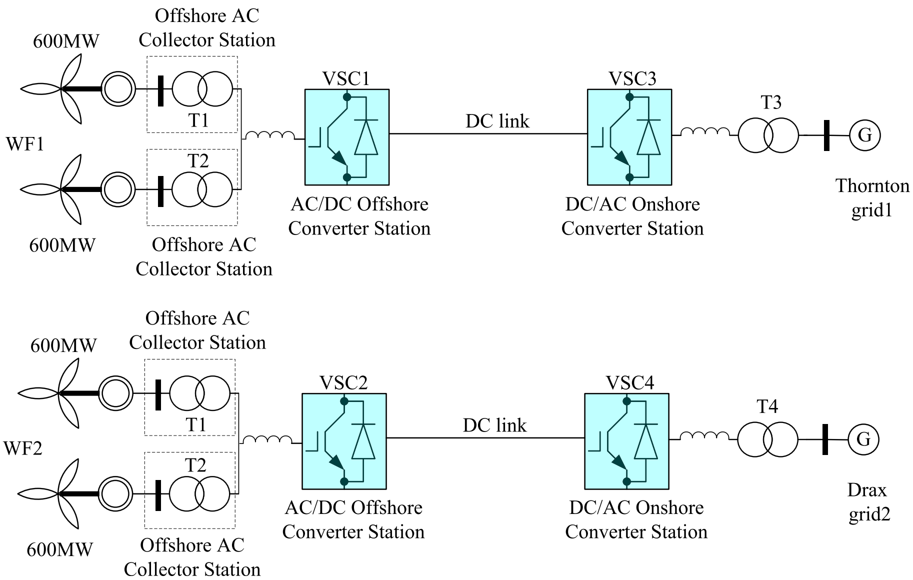


**Fig. 2.** Simplified schematic of two point-to-point connections, based on National Grid connection study [21].

wind farms. This creates increased system flexibility which will be crucial for meeting future energy demands and Grid Codes.

- There is no need to change voltage polarity for power reversal.
- Unlike an LCC-HVDC system, a VSC-HVDC converter is capable of providing reactive power control, frequency control and oscillation damping. There is therefore, no need to implement costly reactive compensation.
- VSC-HVDC connections eliminate the requirement for a start-up generator in the offshore wind farm network as power flow can be reversed to provide start up power from the mainland. LCC-HVDC systems are unable to provide this inherent black start capability.
- A VSC-HVDC system involves a lower investment cost and smaller space requirements compared to traditional LCC HVDC.
- As the use of VSC-HVDC eliminates the need for AC and DC filters and reactive power compensation there is a smaller footprint per station.

### *3.1. Case 1 – Cost estimations*

The cost of the VSC-HVDC point-to-point transmission system consists of: the two offshore converters stations; the HVDC subsea cables linking the wind farm converter stations to the shore; the onshore converter station which assumed to be located close to the shore, the HVAC underground cables; the on-shore civil structures; and the associated construction costs. The estimated total cost of transmission system based on two VSC-HVDC point-to-point systems is £1.88 Billion. This compares with the £4.16 Billion cost of the wind farms themselves. As such the point-to-point connection option represents 31% of the total cost of the project to build and connect the 2.4 GW wind generation on Dogger Bank. Fig. 3 shows the breakdown of the costs associated with the point-to-point connection in millions of pounds.

The greatest cost in the complete project comes from the installation of the wind turbines which constitute around 52.4% of the total cost of the works as shown in Table 3. The price of offshore wind turbine is assumed to be £1320 per kW according to [31] and [22], the offshore wind turbines are still very expensive as the market is limited to a number of manufacturers specialising in this area. The total cost of four converter stations (2 onshore, 2 offshore) and offshore AC platform comes to nearly 21%. AC and DC cables are another large expense and together represent 26.5% of total costs including array cables within the wind farm and transmission cables onshore and offshore. After defining installation costs of the plant, additional costs such as transportation and accommodation are added. There is a requirement for onshore substation network reinforcements such as: substation extensions and reconfiguration, new connection protection and land purchase. These additional costs are the same for all three options and are explained further in Ref. [21]. The latter costs have been verified through consultation with leading GB companies with experience in such work. The cost presented does not include inflation, commissioning costs, design costs, financial risk, or legal costs. The cost for offshore accommodation, transport, operations and maintenance infrastructure has been considered in each option.

## 4. Case 2 – Multi-terminal VSC-HVDC connection

The multi-terminal VSC option involves adding an additional HVDC cable linking the two point-to-point connections of the base case scenario as shown in Fig. 4. In such a topology it often assumed that direct current circuit breakers (DC-CBs) are required to protect the network. It would be possible to protect the full system using AC side protection only so long as the converters have appropriately sized anti-parallel diodes to handle the high fault currents that would flow during the period of up to 100 ms that it would take the AC protection to isolate the DC system from the onshore grid. However, such a method of protection would require the temporary shutdown of the whole DC grid which for the 2.4 GW system being investigated could potentially mean an unacceptable breach of the maximum infrequent loss of load limit for the GB which is currently set at 1800 MW [32], so it is considered inappropriate. Alternative protection strategies involving converter topologies that have reverse current blocking capability or that use a reduced number of DC-CBs have also been explored, for example in Refs. [33], although this paper assumes DC-CBs are used. The cost of DC-CBs remains relatively uncertain as they are yet to be put into production. In this paper the cost of the HVDC circuit breakers is estimated at 1/6 of the full cost of VSC-HVDC converter station in line with other work

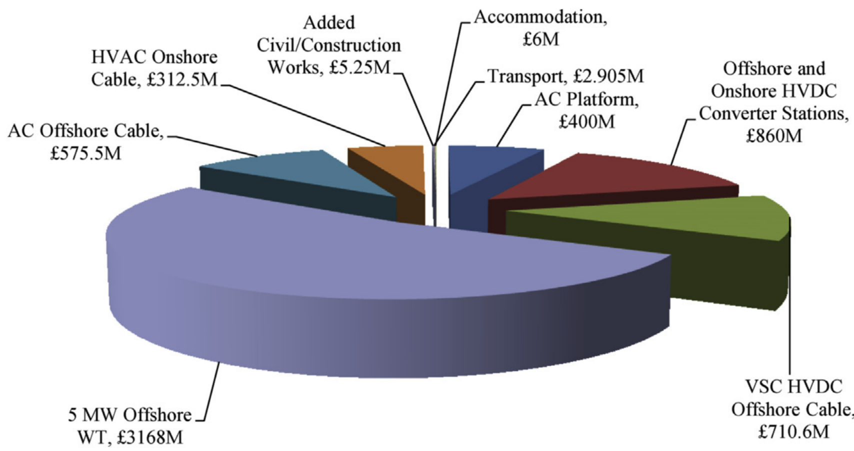


**Fig. 3.** Total cost of construction of 2.4 offshore wind farm and point to point VSC-HVDC transmission connection to mainland GB in £M.

**Table 3**
Cost weighting of each item as a percentage of total cost in £M.

| Item | Percentage of total cost |
|---|---|
| AC Platform | 6.6% |
| Offshore and Onshore HVDC Converter Stations | 14.2% |
| VSC HVDC Offshore Cable | 11.8% |
| 5 MW Offshore WT | 52.4% |
| HVAC Offshore Cable | 9.5% |
| HVAC Onshore Cable | 5.2% |
| Added Civil/Construction Works | 0.09% |
| Transport | 0.10% |
| Accommodation | 0.10% |

in this field [34].

The multi-terminal VSC-HVDC option presented here provides all the benefits of the point-to-point connection and has additional advantages in terms of reliability and controllability [35]. It is expected that a large number of wind farms will be developed on Dogger Bank, dispersed over a wide area. Multi-terminal VSC-HVDC provides a potential solution to the issue of collection and transmission of large amounts of wind power from geographically dispersed wind farms as opposed to the traditional option of using many point-to-point VSC-HVDC links. The main advantages of multi-terminal connections compared to point-to-point connections are [35,36]:

- Improved system reliability and stability during loss of a single DC link.
- The ability to maintain electrical connection to both wind farms during the loss of a single DC link ensuring the ability to continue transferring some power from both wind farms to the GB grid.
- Multi-terminal VSC-HVDC connection increases the power flow controllability between different desired routes.
- Provides the ability to link offshore wind to multiple national AC power networks as part of a 'Supergrid'.

### 4.1. Cost of multi-terminal VSC-HVDC case

The multi-terminal VSC-HVDC option involves two major additional costs: the DC circuit breakers and the additional HVDC

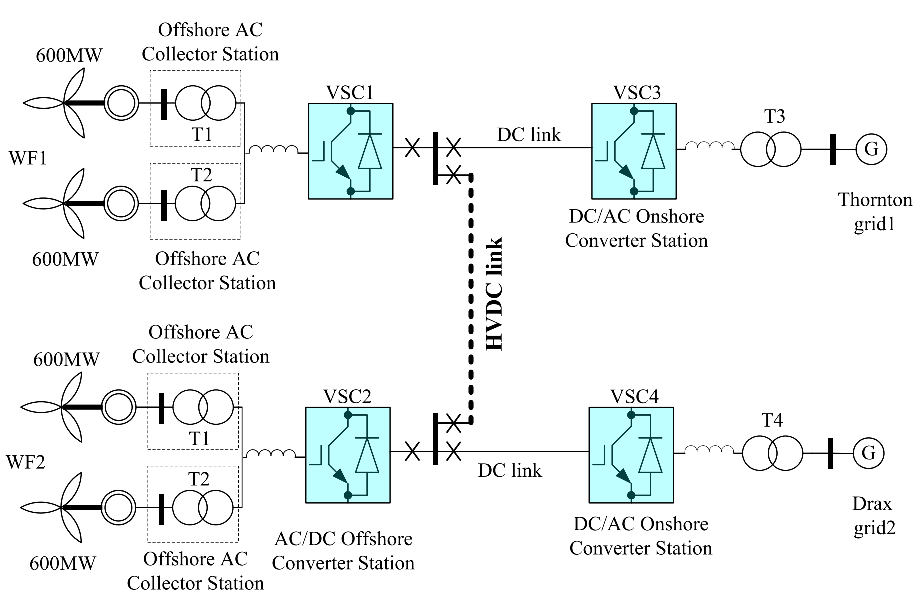


**Fig. 4.** Multi-terminal VSC-HVDC connection with DC-CBs.

cabling linking the converter stations at the two wind farms. Additional cable costs for the 75 km connection between the DC platforms equates to £165million. The DC circuit breakers are assumed to cost £342 million for 12 DC circuit breakers in total, that is 1/6 of the cost of the HVDC offshore converter station [34]. Therefore the total cost of the multi-terminal VSC-HVDC option is £6.55Billion, an increase of £0.50 billion or 8.4%, over the simple point-to-point connection.

## 5. Case 3: point-to-point connection with an auxiliary cable

This option reverts to the point-to-point HVDC connection of option 1, and adds an AC link between the two wind farms shown in Fig. 5. The auxiliary AC cable provides a link between the two offshore converter stations and provides many of the benefits of multi-terminal VSC-HVDC option without the need for DC circuit breakers.

The advantages of the auxiliary AC cable option are:

- During emergency conditions such as maintenance of one of the transformers, one of the 2 offshore HVDC converter stations or sudden loss of dc cables, an additional route is available to transfer some power to the GB grid
- There is no need for DC circuit breakers and this option could be delivered using relatively cheap and proven technologies.
- Additional benefits in terms of security of the system; power can still be transferred in the event of the loss of an offshore converter unlike the multi-terminal HVDC option.

### 5.1. Costs of auxiliary AC cable option

The initial investment costs are higher compared to the point-to-point connection due to the cost of additional AC cable (75 km) and additional AC breakers. The cost of the additional AC cable is assumed to be £187.5 million. The estimated cost of this option is £6.22 Billion, an increase of £187.5 million compared with the base-case but £319 million less than the multi-terminal VSC-HVDC option.

**Table 4**
Additional costs relative to the base case[a] in £billion.

| Option | Multi-terminal connection | AC auxiliary cable |
|---|---|---|
| HVDC cable | £0.165 | 0 |
| HVDC breakers | £0.342 | 0 |
| HVAC offshore cable | 0 | £0.187 |
| **Total Cost** | £6.55 | £6.22 |
| **Percentage increase** | 8.3% | 3.1% |

[a] Base case scenario £6.04 billions.

## 6. Summary of option costs

Table 4 shows a cost summary of the three connection options. Two separate point-to-point connection is the cheapest with a total cost of £6.04 Billion. This option is therefore both technically viable and economically attractive in terms of capital cost.

The multi-terminal connection is the most expensive option at £6.55 billion, an increase of 8.3%. This option provides the possibility of future expansion of the HVDC grid, and has at the same time high security and reliability performance. Whilst DC-CBs are not currently commercially available, they are expected to become available in the near future so this option should be technically viable in coming years although a greater level of capital expenditure will be required.

The point-to-point connection with AC auxiliary cable comes to £6.22 billion, which is an increase of 3.1% compared with the point-to-point connection option. It represents very promising connection architecture if distance between wind-farm substations is small enough. This option is also technically viable using existing commercially available technology and requires a smaller capital expenditure than the multi-terminal HVDC option. It also has the added benefit of securing power transmission even during maintenance or a fault at one of the converter substations.

## 7. Reliability investigation

To evaluate the full cost implications of the three separate design options an investigation of the reliability performance of each is required. The aim of the investigation is to assess how each option is capable of dealing with a lifetime of expected fault

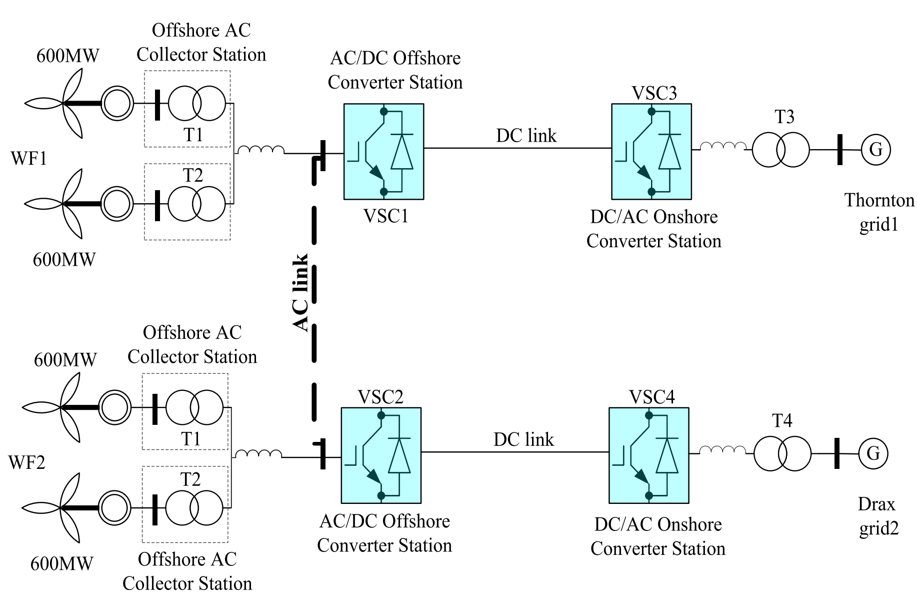


**Fig. 5.** point to point connection with auxiliary cable.

conditions and to calculate the associated expected levels of energy not supplied. To do this the bespoke software tool described in Ref. [37]is used to consider how the three Dogger Bank scenarios perform given a particular set of input reliability assumptions.

### 7.1. Methodology

This section will briefly outline the main features of the reliability study performed although a more detailed description of the methodology can be found in Ref. [37]. The reliability study is based on a Sequential Monte Carlo simulation process whereby faults relating to all major HVDC transmission components are introduced into the network in a random but chronological order with the resulting impacts on grid configuration and energy transmission calculated. The tool makes use of simulated mean wind speed time series to calculate the level of any energy not delivered due to faults on the HVDC network and in conjunction with this it uses concurrent and correlated mean significant wave height time series to help calculate the repair times for offshore components. The simulated wind speed and wave height time series are derived through a multivariate auto-regressive based analysis of real data from the FINO1 offshore measurement station as outlined in Ref. [38]. In doing so, the tool takes account of the realities faced in terms of offshore O&M that mean component repairs can only be carried out when the sea state is within acceptable limits for access. The limits applied are 1.5 m wave height for transmission branch and offshore converter or circuit breaker based repairs and 2 m for offshore transformer repairs as outlined in Ref. [38]. Cable repairs and transformer repairs are assumed to require a single continuous fixed length weather window in order for repairs to be applied whereas other platform based repairs can be carried out over multiple available weather windows if necessary. The nature of the methodology captures the fact that repair times tend to be longer in winter months than in the summer months, when wind speeds tend to be higher and so potential energy capture is highest. As well as capturing the seasonal influence on repair times and so undelivered energy, the model incorporates a number of other features such as fixed delays to repair times when large offshore components such as transformers or specialist vessels (e.g. for cable repair) have to be procured.

### 7.2. Reliability input assumptions

The reliability analysis considers the potential for faults on all major components associated with the HVDC network. Faults are not applied to the internal wind farm network and so available energy is assumed to be 100% up to the point of connection with the HVDC network. The exception to this is Case 3 which makes use of an auxiliary AC connection between the two wind farms which has been included within the fault analysis. Table 5 gives a breakdown of the input mean time to fail (MTTF) values used as input to the reliability study along with the required time to repair (RTTR) values, which relate to the number of working hours required to carry out the repair or the size of the required weather window if a single continuous repair is required, and the fixed delay associated with each fault type. The reliability inputs used are a central case estimate derived from consideration of the range of published projections for component failure and repair rates given in Refs. [39–42] and through discussion with industry experts. For lack of more informed data it is assumed that both AC and DC circuit breakers have the same reliability characteristics. In this study only a central reliability case scenario is examined although it must be noted that a more thorough analysis might consider a range of input scenarios for comparison.

**Table 6**
Annual average available energy not delivered due to faults on HVDC network.

| | Base case | MT HVDC | Auxiliary AC link |
|---|---|---|---|
| Undelivered Energy | 3.94% | 2.90% | 2.14% |
| Annual Cost of Undelivered Energy | £42.06 m | £30.96 m | £22.89 m |

### 7.3. Results

Table 6 shows the results of the reliability analysis using a 100000 year sequential Monte Carlo simulation with the reliability input assumptions outlined in Table 5. The results show that use of an alternative transmission path gives significant benefits in terms of deliverable energy. It is found that the Method using the AC link has the best reliability performance followed by the Multi-Terminal VSC-HVDC option. The expected level of undelivered energy each year is significantly higher under the base case scenario with no inherent redundancy or alternative transmission paths for re-routing power in the event of faults on the HVDC network. To fully appreciate the financial implications of these findings an estimate can be made as to the cost of this undelivered energy assuming that the value of offshore wind electricity is £120/MWh which is in line with the guaranteed strike price agreed for the largest UK offshore wind farm currently in development. The results are shown in Table 6.

To understand how the cost of reliability impacts the overall finances of an offshore wind project the Net Present Value (NPV) of the undelivered energy can be calculated over the expected lifetime of the project. This has been done for a 25 year period using a standard discount rate of 6%. The value of energy delivered from each grid can then be calculated by subtracting the NPV of undelivered energy from the NPV of total expected generated energy over the 25 year period with a calculated capacity factor of 42.3%. Subtracting the total project costs from this value then gives a figure for the NPV of the project as a whole. The results of this analysis are shown in Fig. 6.

This reliability analysis shows that the base case network incurs the highest level of energy curtailment and therefore has the lowest NPV of expected delivered energy over the assumed 25 year project lifetime. The multi-terminal VSC-HVDC makes significant savings

**Table 5**
Reliability input assumptions for HVDC network components.

| Component | MTTF (Hrs) | Repair time (Hrs) | |
|---|---|---|---|
| | | Fixed delay | RTTR |
| Onshore Converter | 7200 | – | 6 |
| Offshore Converter | 7200 | – | 6 |
| Onshore Transformer | 438300 | 2160 | 72 |
| Offshore Transformer | 350640 | 2880 | 120 |
| Transmission Branch | 219150[a] | 2160 | 144 |
| AC and DC Circuit Breakers | 219150 | – | 6 |

[a] Transmission branch – Hrs/100 km.


**Fig. 6.** Cost analysis for a central case reliability evaluation.

in terms of curtailed energy when compared with the base case scenario so the NPV of expected delivered energy is around £150 million higher over the project lifetime. This is not however enough to balance out the extra £507 million capital cost of the project so the multi-terminal VSC-HVDC option has the lowest overall project NPV and is therefore the least value for money option overall. The AC Auxiliary option has the lowest level of curtailed energy and so the highest value of delivered energy worth around £260 million more than the base case option. The option also has lower capital cost than the multi-terminal VSC-HVDC grid with additional costs over the base case of £187 million. It therefore has the highest total project NPV by a margin of over £70 million and so is the best value for money option of those considered. For the reliability scenario investigated it is found that there is high value in having an additional redundant transmission path however it has been shown that the overall cost effectiveness of this depends on the capital expenditure needed to implement the redundancy.

It must be noted that the results of this study are heavily dependent on the input assumptions used and a different set of assumptions could easily lead to different headline results. For example if a more optimistic set of reliability inputs were used which assumed that failure and repair rates could be reduced then the importance of undelivered energy to the overall cost could be significantly lower. This could, for example, mean that the base case, point to point network would remain the best value for money due to its significantly lower capital costs. The opposite is also true in that worse reliability performance of network components would emphasise the benefits of the systems incorporating redundant transmission paths. Further to this if the cost of DC breakers could be reduced to a more manageable level then the value for money of the MT-HVDC option could potentially be brought in line with the auxiliary AC cable option. Another variable which could alter the final results is the distance of the additional transmission path which in this case study is towards the upper limit of AC capability. It is conceivable that connections could be significantly shorter than this in clustered wind farm scenarios and this would reduce the capital cost of building in the redundancy using either method. This would further improve the overall cost effectiveness of the schemes incorporating redundancy. A full sensitivity analysis to failure and repair rates, component costs, transmission distances and cost of energy would be required to fully inform on which network options are likely to provide the most cost effective solutions, however results are likely to be specific to each offshore network case study examined.

To further inform the investigation a number of additional factors could be considered further in future work. These include: the impact of electrical network losses on the overall delivered energy; the possibility of using more complex transmission methods, for example, bi-pole connection of VSC converters; the use of alternative protection strategies such as the use of DC breakers in a limited number of selected locations, perhaps in conjunction with reverse current blocking converters [33]; the possibility of incorporating a spares program to reduce repair delays; and the possibility of making anticipatory investment in offshore infrastructure to allow for future connection of additional offshore wind farm developments. The issue of anticipatory investment would itself raise further questions relating to the need to oversize particular components, how that process would optimised and how the risk of stranded assets are accounted for. Such issues are yet to be fully addressed in the literature but have been discussed in more detail in Ref. [43].

## 8. Conclusion

The importance of HVDC technology is emphasised by the continued growth of renewable energy generation and in particular the potential for large far-offshore wind farm developments. VSC-HVDC is one solution to the challenge of integrating offshore wind power for Dogger Bank in the North Sea, and one that provides the opportunity to develop offshore-network topologies that support reliability of operation in order to minimise the impact of faults. This paper identifies three network topologies for which VSC is suitable: point-to-point connection, Multi-terminal VSC-HVDC and a four terminal VSC-HVDC system with the use of AC axillary cable between offshore wind farms.

Point-to-Point systems are well understood and already used in connecting offshore wind power to the onshore grid in Germany. This option is shown to have the lowest capital cost of the options investigated in this study but does not provide the contingency to make it a highly reliable source of generation. Should one of the terminals experience an outage or if the DC transmission link were to fail then transmission to the onshore AC regional systems would be lost completely. This has also cost implications in that over the course of an expected project lifetime the level of undelivered energy will rise and therefore lost revenue will be high.

Multi-terminal VSC-HVDC arrangements provide valuable flexibility to developments like Dogger Bank as it can provide contingency against certain faults. This studies have shown the costs of multi-terminal-HVDC are very high and do not outweigh the benefits of additional revenue through continued operation under certain fault conditions. One of the key reasons for this, is the high projected cost of DC breakers, however if DC breaker costs came down then it could be a more competitive option.

In the multi-terminal HVDC option, power can be delivered to the onshore grid when one of the onshore converters station is not in operation or one of the transmission line fails, however both offshore station need to be in operation. This has been shown to significantly reduce the level of undelivered energy compared with the Point to Point grid option. Although there is still a need for larger size HVDC cables and HVDC circuit breakers which are not commercially available yet and are likely to come at a high capital cost. The use of a multi-terminal connection topology includes the potential for future interconnection of Dogger Bank with other offshore wind installations or even onshore connection to other countries, which would allow for power trading between regions, hence could have additional economic benefits.

Option 3, where there is an auxiliary cable on the AC side, shows that an economic advantage when the additional costs are compared against the additional revenues from the ability to continue operating the wind farms whilst faults are being repaired. The AC auxiliary cable can redirect power to the other converter station during a fault. Using an auxiliary cable on the AC side is advantageous as it means any of the (onshore or offshore) converter stations or one of the transmission line can be under maintenance or out of order while power can still be delivered to the onshore grid. Hence this option is the most reliable of those investigated and due to the use of established technology the capital costs are also relatively low. However the use of this option is limited by distance, as losses in AC cables can become prohibitively high at distances beyond those investigated in this study. This option also has the potential to oversize the whole system to allow additional power from other wind farms.

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